STREAM FLOW REGIME, TEMPERATURE AND CLIMATE CHANGE: THE LOSS OF FISH HABITAT

JOSÉ M. SANTIAGO
JOAQUÍN SOLANA
CARLOS ALONSO
DIEGO GARCÍA DE JALÓN
Laboratory of Hydrobiology. Universidad Politécnica de Madrid, ETSI Montes, Avda. Ramiro de Maeztu S/N, Madrid 28040, Spain

RAFAEL MUÑOZ-MAS
FRANCISCO MARTÍNEZ-CAPEL
Institut d'Investigació per a la Gestió Integrada de Zones Costaneres (IGIC), Universitat Politècnica de València. C/ Paranimf 1, Grau de Gandia, València 46730, Spain

JAIME RIBALAYGUA
JAVIER PÓRTOLES
ROBERT MONJO
Fundación para la Investigación del Clima. C/ Tremps 11. Madrid 28040, Spain

This study is aimed at forecasting the changes in the suitability of brown trout habitat (*Salmo trutta* L.), caused by alterations in the stream temperature and the flow regime under climate change scenarios. The stream temperature and instantaneous flow in several streams in Central Spain were modelled from daily temperature and precipitation data. Logistic models were used for stream temperature modelling whereas M5' model trees were used to develop the precipitation-runoff models. These models were utilized to simulate the running flows under the climate change scenarios RCP4.5 and RCP8.5 (5thIPCC). The resulting forecasts suggested a different response of the stream temperature to the atmospheric warming in accordance with the geologic nature of basins. At the same time, significant decreases in summer flow and increases in the frequency of zero-flow events were predicted. In the future, significant declines in summer flow could exacerbate the negative impact on trout populations of increased water temperature by reducing both the suitable spatial habitat and the warming resistance of the water mass.

1 INTRODUCTION

Natural patterns of water temperature and stream flow are profoundly linked with current climate. Consequently both, the predicted increments in air temperature and decrements in the precipitation by climate change may turn in significant alterations in flow and thermal regimes and thus, these alterations are likely to paramountly disturb aquatic ecosystems. Climate change may affect habitat availability for many fish species by increasing or reducing both, spatial and thermal habitat. Habitat suitability modelling based on climate scenarios can help scientists to assess the magnitude of these changes on the suitable range, especially in these areas at the warm and dry edge of their native distribution as it is the brown trout (*Salmo trutta* L.) case.

The main goal of this study is to know how climate change will affect brown trout habitat availability. For that purpose, air temperature and precipitation in two climate change scenarios were modelled in a daily time-step the water temperature and the flow rate at 13 streams (28 sites) of five fluvial basins in the centre of the Iberian Peninsula. Flow was modelled by means of M5' model trees and the water temperature by means of nonlinear regression. The habitat suitability change was assessed by deviations from trout thermal niche and physical space loss due to flow reductions.

2 MATERIAL AND METHODS

The study sites were selected to encompass a diverse array of hydrological and geological conditions. In the end, 13 mountain streams of central Spain (between 39º53' N and 41º21' N latitudes) were the subject of temperature and flow modelling, namely: Tormes stream and its tributaries Barbellido, Gredos Gorge and Aravalle (Duero basin), Cega, Pirón (Pirón stream is tributary of Cega stream, in the larger Duero basin), Lozoya, Tagus, Gallo, Cabrillas (Tagus basin), Ebrón and Vallanca (Vallanca stream is tributary of Ebrón stream, in the Turia basin)

(Figure 1). Major components of geology characterize mountain sites in Duero basin and Lozoya basin as granitic, lower elevation sites in Duero basin are Cenozoic (detritic), and eastern basins are characterized as Mesozoic (mainly karstic).

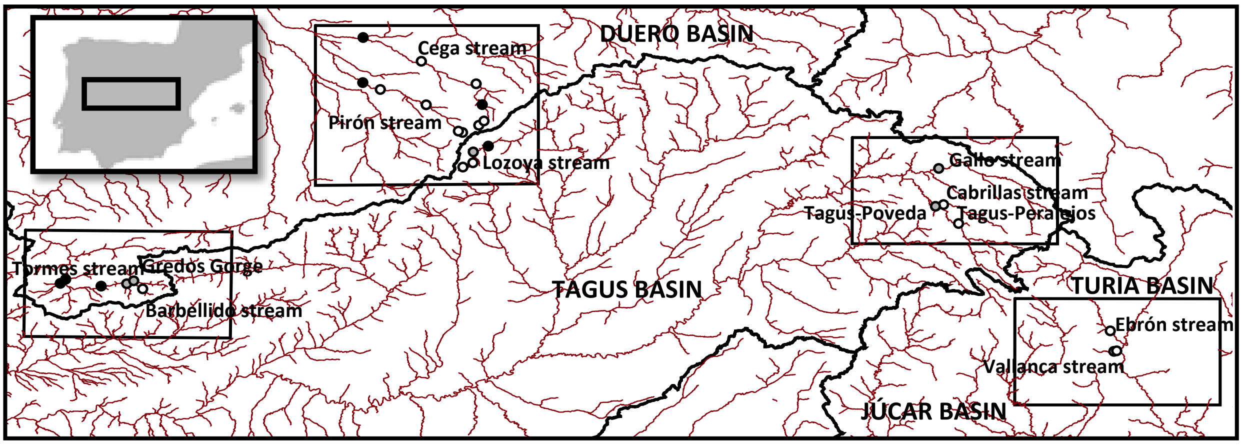

Figure 1. Study area and thermograph sites. Dots show sites in which water temperature threshold (18.7ºC) was predicted not to be overpassed during seven or more consecutive days (blank) in any climate change scenario (RCP4.5 and RCP8.5), to be overpassed in both scenarios (solid), or to be only overpassed in the RCP8.5 scenario (shadowed). Sites numeration in the main text was done from upstream to downstream. Predictions were built by using the model by Santiago *et al*. [8].

Air temperature and precipitations were used as inputs for water temperature and flow modelling which were calibrated on the instant flow series and dedicated measures of water temperature. Meteorological data were obtained from six thermometric and 11 pluviometric stations of the Spanish Meteorological Agency (AEMET) network whereas eight gauging stations (official network) were used for studying and modelling flows. Finally, water temperature was registered every two hours using 28 Hobo® Water Temperature Pro v2 (Onset®) thermographs located at several sites along the studied rivers (Figure 1).

Data from nine global climate models associated with the 5th Coupled Model Intercomparison Project (CMIP5) were used (BCC-CSMI-1, CanESM2, CNRM-CM5, GFDL-ESM2M, HADGEM2-CC, MIROC-ESM-CHEM, MPI-ESM-MR, MRI-CGCM3 and NorESM1-M) to forecast future climate change corresponding to the Representative Concentration Pathways RCP4.5 (stable scenario) and RCP8.5 (more increasing emissions scenario) established in Taylor *et al*. [1] and used in the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC [2]). Climatic predictions were properly downscaled for each station in a daily time step following a two-step analogue statistical method [3].

The precipitation-runoff models were developed by means of M5' model trees [4] in R with the package Cubist [5]. The main difference with other tree-based approaches relies in the ultimate prediction at the leaves, since M5' implements a linear model instead of an average prediction. The resulting model can be seen as a modular model with the linear models being specialized on the particular subsets of the input space [6]. These linear models at the branches confer to M5' the capability for extrapolation in contrast to some other machine learning techniques that demonstrated poor or null capacity for it [7]. Tormes and Ebrón basins were not modelled for this study. The input variables (i.e. daily, monthly and quarterly lagged temperature and precipitation) were selected following the step-forward approach with fivefold cross-validation whereas the objective function was the Nash-Sutcliffe efficiency (NSE). These models were used to simulate the flow rates under the climate change scenarios.

Daily mean stream temperature and events of 7 consecutive days above a daily mean threshold (18.7ºC) representing the realized niche was used to assess the thermal impact of climate change [8]. A modified Mohseni's *et al*. [9] model including a trajectory of temperature to improve the daily predictions [8] was used to model the thermal behaviour. In addition, the model was further modified by introducing the daily mean flow (Q) through a logistic function with three parameters (ω, δ, τ). Non-linear regression was used to estimate the parameters of both modified Mohseni's models (with and without flow), and bootstrap techniques were used to avoid the autocorrelation effect on the parametric signification. The Bayesian information criterion (BIC) and Akaike information criterion (AIC) were used to test the modified model.

The decadal average (period 2090-2099) of days above the 18.7ºC threshold per year (DAT), events of 7 or more consecutive days above the threshold per year (TAT≥7), and maximum consecutive days above the threshold per year (MCDAT) were modelled in each study site for each climate change scenario to assess the impact on the thermal habitat [8].

Spatial habitat suitability changes (weighted usable area -WUA-) were quantitatively estimated for summer time in representative reaches in Lozoya and Cega streams by means of River2D software. Current flow and two predicted flow scenarios (RCP4.5 and RCP8.5) were used to simulate three different habitat suitabilities.

3 RESULTS

3.1 Climate change

Under the climate change scenarios, all the meteorological stations showed an important thermal increase throughout the century, more pronounced in RCP8.5 scenario, being larger in summer and smaller in winter. Precipitation remained without significant variations in RCP4.5 scenario. Most important changes were predicted to be in summer and autumn in the RCP8.5 scenario.

3.2 Runoff

M5'-based precipitation-runoff model performed well in any case (NSE: Cega-Pajares, 0.780; Cega-Lastras, 0.930; Pirón, 0.793; Lozoya, 0.842; Tajo, 0.728; Gallo, 0.797; and Cabrillas 0.790).

In the RCP4.5 scenario, the most remarkable and significant results suggested an annual runoff loss of by 17% in Pirón by the end of the century, being followed by Tagus (-13%) and Lozoya (-12%). Gallo, Cabrillas and Cega-Lastras showed smaller reductions than 10%, and Cega-Pajares did not achieve significant changes. The most significant flow losses in Pirón stream occurred mainly in spring (e.g. mean flow Qm: -28%), but in Cega-Lastras it occurred in summer (Qm: -37%). Main flow losses were predicted for summer and autumn in Lozoya stream, for spring in the Tagus River, and for spring and autumn in Gallo stream. The flow reductions were proportionally similar during the whole year in Cabrillas stream, but they were slightly more pronounced in winter and summer. Conversely, significant flow losses did not predicted in Cega-Pajares. Finally, at Cega-Lastras, Gallo and Pirón gauging stations, an increasing frequency of zero-flow days was forecasted.

In the RCP8.5 scenario, the results suggested an annual runoff loss in Pirón (-49%), Lozoya, Cega-Lastras and Tagus gauging stations (from -30 to -40%), whereas the reductions were below -20% in Gallo, Cabrillas and Cega-Pajares sites. Pirón, Lozoya and Cega-Lastras forecasts were the highest the whole year, but relative summer flow losses were more important in Lozoya and Cega-Lastras while they were the lowest in summer in Pirón site. The forecasted flow losses were only significant in autumn (relatively more important) and winter in Cega-Pajares. Flow losses were predicted to be fairly constant the whole year in Gallo and Cabrillas while, in the Tagus River, they were more important in winter and spring but lesser in summer. Finally, zero-flow days were especially predicted to increase in Cega-Lastras (332%), Gallo (204%) and Pirón (117%). This variable did not change in forecasts on Tagus River, Cabrillas and Lozoya gauging stations.

3.3 Stream temperature

In accordance with the BIC and the AIC calculated for every temperature model, the inclusion of the running flow improved models' performance in 12 out of 28 study cases. Five parameters model was used in the 16 cases in which flow did not involve any improvement.

In the whole sample, Pearson correlation between thermal amplitude (α-μ of Mohseni's et al. [9] model) and λ (parameter of resistance to the thermal change in Santiago *et al*. [8] model) was significant (-0.800; p<0.0001). The greater the thermal amplitude, λ was more negative (less resistance). The lower thermal amplitude, λ was closer to zero (more resistance). Correlation was also significant between λ and β (-0.473; p=0.011), λ and ω (-0.789; p=0.002), and the thermal amplitude and γ (-0.454; p=0.015). β values were higher in igneous ($\bar{\beta}$= 12.71) than carbonated sites ($\bar{\beta}$= 7.80) (t-test with Bonferroni correction, p<0.001), and λ was significantly higher ($\bar{\lambda}$= -0.1499) in carbonated than in igneous ($\bar{\lambda}$= -0.2918) and quaternary-detritic sites ($\bar{\lambda}$= -0.3057) (t-test with Bonferroni correction, p<0.01).

On climate change forecasts, 18.7ºC threshold was violated in 7 sites in RCP4.5 scenario, and 12 sites in RCP8.5 scenario (Figure 1). These violations imply the loss of thermal habitat for brown trout.

Flow reduction effect on temperature was analysed in the sites: Lozoya1 to 4, Cabrillas, Cega1 and Pirón1. In all cases stream differences with the 5 parameters model were found but only in Lozoya stream the threshold was overpassed, increasing the thermal habitat loss. Thus, summer flow reduction conducted to a stream temperature elevation and DAT, TAT≥7 and MCDAT increased.

3.4 Physical habitat

A significant decrease in WUA occurred by flow decrease. WUA in Lozoya stream was reduced by 11%, 13% and 21%, and in Cega stream it was by 4%, 4% and 2%, at RCP4.5 scenario for adults, inmature and YOY trouts, respectively. This reduction was by 24%, 27% and 47% in Lozoya stream, and by 15%, 12% and 13% in Cega stream, at RCP8.5 scenario.

4 DISCUSION AND CONCLUSIONS

The method to model the running flows was deemed proficient because all the performance criteria were higher than 0.7. Significant flow reductions were forecasted at all basins. The largest would be experienced in the Pirón River. Stream temperature model were found robust. The models' parameters described accurately the thermal performance of the study sites, and relations among parameters, geology and hydrologic response were found. The forecasted increase on water temperature was quantitatively important in most of the study sites. A group of streams showed sensitivity to the flow introduction in the temperature model. In these streams, differences between the estimated stream temperature by both models (with and without flow) were important, and summer flow reductions conducted to an additional stream temperature increase. The most deep-aquifer dependent sites better resist warming (Mesozoic basins). Summer flow reductions influenced again on trout habitat by reducing WUA. In accordance with the herein presented results, the forecasted flow reductions and water temperature increases drive to important suitable fish habitat losses, especially for cold water fish like brown trout.

5 ACKNOWLEDGMENTS

We are grateful to the Consejería de Medio Ambiente y O.T. of the Government of Castilla y León (especially to M. Anchuelo, F. Mateo and the forest ranger team of Navafría). Also, we are in debt to the Sierra of Guadarrama National Park staff, (especially to J. Bielva and Á. Rubio) for the temperature data of Lozoya stream. J.D. Alcaraz is the author of the temperature data of the Ebron basin. The World Climate Research Programme's Working Group on Coupled Modelling is responsible for the CMIP5, and we thank them for producing and making available their model output. Climate change study was partially funded by the Ministrerio de Agricultura, Alimentación y Medio Ambiente and by the 7th Framework Programme of the European Union (DURERO Project. C1.3913442).

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